Effects of soil moisture and soil depth on nitrogen mineralization process under Mongolian pine plantations in Zhanggutai sandy land, P. R. China

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Abstract: The rates of soil N mineralization at soil depths of 0–15, 15–30, 30–45 and 45–60 cm and moisture regimes were measured at three sand-fixation plantations of *Pinus sylvestris* var. *mongolica* by laboratory aerobic incubation method. The results showed that average rates of soil net N-mineralization across soil depth varied from 1.06 to 7.52 $mg \cdot kg^{-1} \cdot month^{-1}$ at soil depths from 0 to 60 cm. Statistical analyses indicated that the effects of different soil depths, moistures and their interactions on net N-mineralization rates were significant ($P < 0.05$). The net N-mineralization rates significantly decreased with increasing soil depths and at depth 0–15 cm accounted for 60.52% of that at depth of 0–60 cm. There was no difference in soil net N-mineralization rates between half and fully-saturated water treatments, however these rates were substantially higher than that without water treatment ($P < 0.05$). The factors influencing N mineralization process have to be studied further in these semiarid pine ecosystems.

Keywords: Laboratory aerobic incubation method; Nitrogen mineralization; Management practices; Sand-fixation forest; Semiarid region; *Pinus sylvestris* var. *mongolica*; Soil depth

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Introduction

Water and nitrogen (N) are considered as two key factors limiting productivity of most arid and semiarid ecosystems around world (Schlesinger *et al.* 1990; Hooper *et al.* 1999). Little has been known about the influence of soil moisture on N availability in semiarid ecosystems on sandy soils, although many reports showed there existed feedbacks among soil N mineralization, N availability, soil moisture and plant water use efficiency in other ecosystems (Binkley *et al.* 1989). For better managing semiarid and arid ecosystems and sustaining their stability, it is necessary to better understand water dynamics and nutrient cycling processes. Practically, there appeared many problems about artificial vegetation construction (Dugald *et al.* 2002). For example, many *Banksia* and *Eucalyptus* trees under artificial forests died in eastern Australia (Fansham *et al.* 1999; Groom *et al.* 2000), and Mongolian pine (*Pinus sylvestris* var. *mongolica*) plantations showed stand decline in Zhanggutai sandy land (Zeng *et al.* 1996). The importance of nutrient cycling in the field of silviculture was neglected in the past. Now, many researchers suggested that the key ecological processes (e.g., N cycling) should be considered as a major index to assess ecosystem function (Loreau 1994; Morris *et al.* 1998).

To promote research and conservational practices against sand storms, soil erosion and desertification, Mongolian pine was introduced as a tree-planting species first time in 1955 to Zhanggutai, the southeastern edge of Keerqin sandy land. Due to its good ecological adaptation at early growth stage, it has been widely used as a good planting-tree species for stabilizing dunes in the northern parts of China (Jiao 1989). In the past 50 years, it was planted in large quantities in Three-North Regions of China, with the encouragement of national afforestation policies and sustentation funds (Chen *et al.* 2002; Jiang *et al.* 2002). However, since the early 1990's, the earlier established Mongolian pine stands started exposing many unstable phenomena such as soil water shortness, dieback, declining productivity and even death in Zhanggutai as well as in other planted regions (e.g., Inner Mongolia, Heirongjiang and Shanxi Province), still with unknown reasons (Jiang *et al.* 2002). It was deduced that water and nutrient deficiency contributed to the decline of productivity and instability (Chen *et al.* 2002). Now, we would not get any concluding reasons behind it due to the absence of convictive experimental information. Therefore it is necessary to investigate the effects of soil moisture on N mineralization rates in the sand-fixation pine plantations.

In this study, we used laboratory aerobic incubation method to estimate soil N mineralization rates at different soil depths and moisture regimes under three sand-fixation plantations of Mongolian pine, with main aims to provide a basis for understanding interaction between soil water and N transformations in Mongolian pine plantations, and to give some research implications for scientifically evaluating afforestation effects and ecosystem stability.

Materials and methods

Study sites

The study was conducted at the Experimental Forest of Liaoning Province Institute of Sand Fixation and Afforestation in Zhanggutai Town (42°43′N, 122°22′E), Zhangwu County, Liaoning Province, southeastern Ke'erqin sandy land, China. The mean altitude of the area is 226.5 m above sea level. The area

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belongs to semiarid. Mean annual precipitation is about 450 mm, with most falling between June and August. The mean annual evaporation capacity is 1300–1800 mm, annual average wind speed was between 4.5–5.0 $m \cdot s^{-1}$ prevailing in winter and spring, and the mean annual temperature is 6.2 °C. The mean annual cumulative temperature above 10 °C was 2890 °C, the relative air humidity was 59%, and the mean annual frost-free period is 150d. The major soil type in this area is aeolian sandy soil, with poor essential nutrients (C, N and P), (Chen *et al.* 2002).

Experimental plots

Three typical Mongolian pine plots (ZSM30, ZSL30 and ZSL47; area for 30 m x 20 m) were selected. They represented two management practices (Non-grazing and free grazing) and two different stand ages (30 and 47 years old). Basic stand characteristics of the experimental sites such as stand density, mean diameter at breast height (DBH), mean height are shown in Table 1, and the soil bulk density, pH value and nutrient concentrations are given in Table 2.

Table 1. Characteristics of the experimental Mongolian pine plantations

Stand	Age (a)	Density ($trees \cdot hm^{-2}$)	DBH (cm)	Height (m)	Management history
ZSM30	30	850	14.35±0.80a*	8.01±0.20a	Non-grazing >4 years
ZSL30	30	825	14.15±0.63a	7.93±0.13a	Free-grazing
ZSL47	47	725	19.28±1.98b	13.46±0.86b	Free-grazing

Notes: *Mean ± 1 SE, n >30; Values suffixed with same letters in the each column are not significant at $P < 0.05$ level.

Table 2. Basic soil characters (0–15cm) in three Mongolian pine plantations

Stand	Bulk density ($g \cdot cm^{-3}$)	pH	Organic C ($g \cdot kg^{-1}$)	Total N ($g \cdot kg^{-1}$)	Total P ($g \cdot kg^{-1}$)	C/N	N/P
ZSM30	1.62±0.01a	6.37±0.07a	3.90±0.14a	0.395±0.038a	0.101±0.007a	9.87±1.94a	3.91±0.98a
ZSL30	1.65±0.01a	6.67±0.05a	3.97±0.08a	0.415±0.006a	0.111±0.002a	9.57±2.17a	3.74±0.98a
ZSL47	1.67±0.03b	6.09±0.11b	7.37±0.50b	0.533±0.008b	0.141±0.001b	13.83±3.65b	3.78±0.76a

Notes: *Mean ± 1 SE, n=6; Values suffixed with same letters in the each column are not significant at $P < 0.05$ level.

Experimental design and analysis methods

Laboratory aerobic incubation method (Binkley *et al.* 1989) was used to assess soil N ammonification, nitrification and net mineralization rates in the summer of 2004. First of all, we divided each plot into six subplots. Second, in each subplot, two soil samples (the distance < 20 cm) were collected from each soil depth at 0–15, 15–30, 30–45 and 45–60 cm, with PVC tubes (diameter = 4 cm, height = 15 cm). Third, 12 soil samples in every soil depth at each plot were transported to laboratory at once with 6 of them for the analysis of initial NH_4^+-N and NO_3^--N and the 6 others for laboratory incubation. Fourth, soil N mineralization rate of each depth was evaluated at three different soil moistures (current soil moisture, 10–20 $g \cdot kg^{-1}$; half-saturation moisture content, 80–100 $g \cdot kg^{-1}$; saturation moisture content, 160–200 $g \cdot kg^{-1}$) in laboratory incubation at 30 °C for 30 days. Each treatment had two replications. Tube mouths were capped by plastic films and ventilated one time each day, and the soil of each sample was kept relatively constant water content by weight. Fifth, after 30 days incubation, the samples were taken out to analyze the final NH_4^+-N and NO_3^--N.

Soil samples were sieved through a 2-mm mesh screen, then 30-g soil of each sample was extracted by 2-$mol \cdot L^{-1}$ KCl of 100 mL, and soil NH_4^+-N was analyzed by phenate method, NO_3^--N by phenoldisulphonic acid method (Liu *et al.* 1996). Soil moisture was measured by oven-dry (105 °C, 24 h). All values are expressed on an oven-dry soil (105 °C, 24 h) basis.

The other properties of soil at 0–15 cm were analyzed at the same time. Soil pH was measured in a 1:2.5 mixture of soil with deionized water using a glass electrode. Bulk density was measured in grams per cubic centimeter ($g \cdot cm^{-3}$). Organic C was determined by dichromate oxidation and titration with ferrous ammonium sulphate. Total N was determined by microkjeldahl method. The total P was determined by nolybdenum blue method (Liu *et al.* 1996).

Data processing

The ammonification and nitrification rates were obtained by subtracting initial quantity of soil NH_4^+-N, and NO_3^--N from their amount of post incubation, respectively. Hence the net N mineralization rate is referred as the sum total rate of ammonification and nitrification in the given time. The computation work was completed using SPSS for Windows statistical software (SPSS 2001).

Results

Multivariate analysis method was used to analyze the interactive influence of soil moisture, soil depth and stand site on N mineralization process (Table 3). Different sites had not significant effect on soil ammonification, but had significant (P<0.001) effect on soil nitrification and net N-mineralization rates. Analysis of variance also indicated that effects of soil moisture and depth treatment on ammonification, nitrification and net N-mineralization rates of pine plantations were significant (P<0.001), and the interactions of the site, soil depth and moisture (soil × moisture, soil × site × moisture) on ammonification, nitrification and net N-mineralization rate were also significant (P<0.05). However the interaction of site and soil depth (site × soil depth) was significant only on ammonification rate (P<0.05), while the interaction of site and soil moisture (site × soil moisture) on nitrification and net N-mineralization rate was significant (P<0.05), (Table 3).

Table 3. Summary of ANOVA results (effects of site, soil depth and moisture) for ammonification, nitrification, and net mineralization rates of soil under Mongolian pine plantations

Factors	Ammonification rate	Nitrification rate	Net N Mineralization rate
Site ($F_{2,36}$)	0.44^{NS}	20.06***	20.14***
Soil depth ($F_{3,36}$)	62.85***	418.72***	355.52***
Soil moisture ($F_{2,36}$)	87.66***	81.56***	48.94***
Site×depth ($F_{6,36}$)	6.26***	1.05^{NS}	1.73^{NS}
Site×moisture ($F_{4,36}$)	0.23^{NS}	11.52***	11.40***
Depth×Moisture ($F_{6,36}$)	2.99*	22.95***	19.66***
Site×depth×moisture ($F_{12,36}$)	3.88**	7.49***	6.75***

Notes: ^{NS} non- significant; * significant at P<0.05 level; ** significant at P<0.01 level; *** significant at $P < 0.001$ level.

Further analysis for effects of soil moisture and depth on the rates of soil ammonification, nitrification and net N-mineralization under different stands showed that the ammonification rates increased with increase of soil depths, except the current water treatment of ZSL30 and ZSL47, but decreased with increase of soil moisture except 30–45 and 45–60-cm soil depths in ZSL30. The nitrification and net N-mineralization rates decreased with increasing soil depths but increased with increasing moisture (Fig. 1).

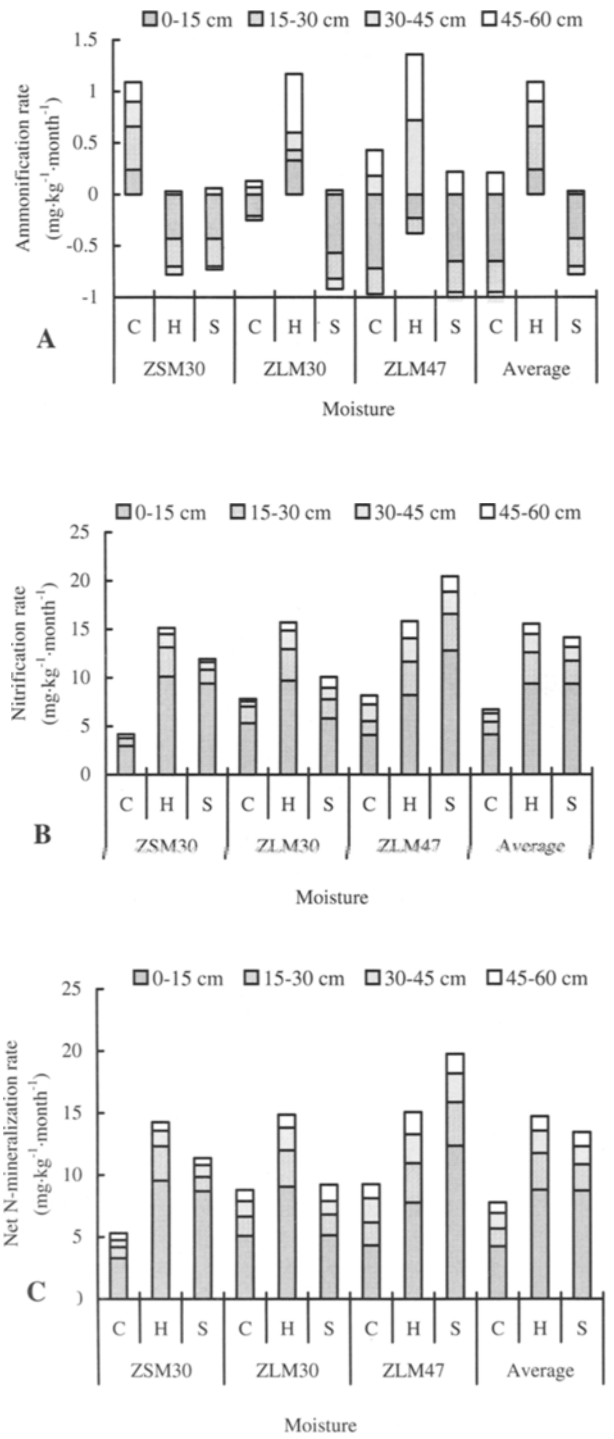

Fig. 1 Effect of soil moisture on ammonification rate (A), nitrification rate (B), and net N-mineralization rate (C) of soil under Mongolian pine plantations (C: current soil moisture; H: half-saturation moisture content; S: saturation moisture content)

Among different sites of Mongolian pine stands, the ammonification rate of soil did not vary significantly while nitrification and net N-mineralization rates of soil showed the following order: ZSM30 < ZSL30 < ZSL47 (P<0.05). As for the different soil depths, ammonification rate increased with increasing depths, while nitrification and net N-mineralization rates showed an opposite trend. Ammonification rates decreased with decrease of soil moisture, but nitrification and net N-mineralization rates showed no difference between half saturation and saturation treatments. However the nitrification and net N-mineralization rates in added water treatments were higher than those of current water treatment (Table 4).

Table 4. Ammonification, nitrification and net N-mineralization rates of soil with different treatments ($mg \cdot kg^{-1} \cdot month^{-1}$)

	Treatments	Ammonification rate	Nitrification rate	Net N-mineralization rate
Sites	ZSM30	-0.02a*	2.60a	2.58a
	ZSL30	-0.06a	2.80ab	2.74ab
	ZSL47	-0.03a	3.70b	3.67b
Soil depths	0-15 cm	-0.35a	7.60a	7.25a
	15-30 cm	-0.14b	2.31b	2.17b
	30-45 cm	0.11c	1.39bc	1.50b
	45-60 cm	0.23c	0.82c	1.06b
Soil moistures	Current	0.27a	1.68a	1.95a
	Half saturation	-0.20b	3.89b	3.68b
	Saturation	-0.17b	3.53b	3.36b

Notes: *Mean ± 1 SE, n= 24 for sites and soil moisture, and 18 for soil depths; Values suffixed with same letters in the each column for sites, soil depths and moistures, respectively, are not significant at P<0.05 level.

Discussion

In general, N mineralization rates decreased with increasing soil depths (Federer 1983; Hadas *et al.* 1989). In this study, nitrification and net N-mineralization rates decreased with increasing soil depth like the general law, while ammonification rate showed an opposite trend. This indicated that the condition with increasing soil depths was disadvantage of nitrification, which resulted in soil NH_4^+-N concentration and ammonification rate increased with increasing soil depths during incubation. Meanwhile, the contributions of every depth for N mineralization rates were recorded at soil depth at 0–15 cm (60.5%) followed by 15–30 cm (18.1%), 30–45 cm (12.5%) and 45–60 cm (8.85%) respectively in all pine stands. These showed that the N mineralization rate at surface soil was exceeded half to the whole soil profile, and the rate rapidly decreased with increasing depth. The percentages of N-mineralization at soil depth of 0–15 cm to that of soil depth of 0–60 cm in ZSM30, ZSL30 and ZSL47 sites were 69.6%, 59.2% and 55.5%, respectively. Therefore, all these revealed that surface soil should be considered as the key part during study on N mineralization.

Evans *et al.* (1998) reported that there was positive correlation between soil net N-mineralization rates and moistures. Stanford *et al.* (1972) found that N-mineralization rates rapidly increased with water potential. However, some reports showed that N-mineralization rates increased with increasing moisture in the initial period, then rapidly decreased with increasing moisture from certain value (Bernhard-Reversat 1988). In our study, soil ammonification rates decreased with increasing moisture, and nitrification and net N-mineralization increased with increasing soil moisture at certain range, then decreased. However, we did

not find the optimal soil moisture due to limited experimental gradient. Therefore it is necessary to make a further study of the effect of soil moisture on N mineralization and its mechanism.

In addition, a similar trend between soil nitrification rate and net N-mineralization rate changed across the stand site, soil moisture and soil depth. Moreover, the percentages of nitrification to net N-mineralization rates under all studied plantations exceeded 75%. All these were related to higher soil pH (>6.0) and chronic human disturbances (i.e., grazing). On one hand, higher pH was advantage to dissolution of organic matter that provided many C and N substrate for microbes, and accelerated N mineralization process (Curtin *et al.* 1998). On the other hand, grazing could cause changes of soil structure and vegetation, such as soil bulk density and water content increase, soil porosity and plant species decrease, root turnover speedup and so on, which was favorable to soil N nitrification (Shariff *et al.* 1994; Evans 1999).

Conclusions

Ammonification, nitrification and net N-mineralization rates of soil were -0.35–0.23, 0.82–7.20, and 1.06–7.25 $mg \cdot kg^{-1} \cdot month^{-1}$ at depth 0–60 cm, respectively, under sand-fixation plantations of Mongolian pine by laboratory aerobic incubation method.

N ammonification rates of soil were insignificant ($P < 0.05$) among plantations, while nitrification and net N-mineralization rates were significantly different between different sites of the plantation. Both of the nitrification and net N-mineralization rates among the different sites showed that the following order was ZPM30 ≤ ZPL30 ≤ ZPL47 ($P < 0.05$), which indicated the positive effects of grazing and stand age on N mineralization rate.

The interactions of soil depth and moisture on ammonification, nitrification and net N-mineralization rates were significant ($P < 0.05$). Ammonification rate increased with increasing soil depths, and decreased with increasing soil moisture; nitrification and net N-mineralization rates decreased with increasing soil depths, and the rates in half-saturation and saturation water treatments were not significantly differed but values for both added water treatment were higher than that of un-added water treatment ($P < 0.05$).

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